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DIFFERENCES BETWEEN ERBE AND CERES TROPICAL MEAN FLUXES: ENSO, CLIMATE CHANGE OR CALIBRATION?

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1. INTRODUCTION

Verner E. Soumi was the father of radiation budget measurements from space. He directed the team at the University of Wisconsin that developed the first radiation budget measurements on the Iota (Explorer VII) spacecraft in 1959 (Weinstein and Soumi, 1961; Soumi and Shen, 1962). The first data published was from hand calculations of night-time long-wave fluxes, with absolute accuracy estimated as better than 10 percent, and the data shown as hand drawn maps with lines of equal "long-wave radiation loss, in Langleys per minute X 10^{-3} (isolangleys)". The first comparisons of the new radiation data with nephanalyses showed that clouds dominated the radiation patterns (Weinstein and Soumi, 1961). Soumi immediately proposed using the radiation fields to help understand the atmospheric heat sources necessary to drive the atmospheric circulation (Soumi and Shen, 1962). This early work already pointed to the relationship between the outgoing longwave radiation at the top of the atmosphere and the vertical flux divergence of infrared radiation within the atmosphere.

In the next 30 years, global satellite observations of the radiation balance of the planet have advanced both in accuracy, stability, and in their ability to address cause and effect in the climate system. The purpose of the present paper is to examine early results of the new CERES (Clouds and the Earth's Radiant Energy System) data on TRMM (Tropical Rainfall Measuring System) which started data collection in January, 1998. CERES is a direct descendant of the legacy of Soumi's foresight on understanding the global energetics using satellite observations of broadband radiation.

2. CERES DATA

The CERES instrument (Lee et al., 1998) is an improved version of the ERBE (Earth Radiation Budget Experiment; Barkstrom, 1984) scanning broadband radiometer. Performance Improvements include (Priestley et al., 1999):

- absolute calibration accuracy estimated as 1% in the SW and 0.5% in the longwave (Lee et. al., 1998),
- consistency of ground calibration and in-orbit calibration to better than 0.25%,
- scan angle dependent offsets reduced by an order of magnitude to roughly 1 digital count (0.2%),
- no discernable change in instrument gains for any channel at the 0.2% level with 95% confidence in the first year of operation.

The CERES scanners are also capable of scanning in either a fixed azimuth (e.g. crosstrack for global coverage) or by rotating in azimuth angle as it also scans in elevation: thereby achieving the first hemispheric broadband measurements since the Nimbus 7 radiometer in 1978/79. CERES is designed to be flown with a cloud imager capable of accurate and stable estimates of cloud fraction, height, optical depth, emissivity, water phase and particle size.

The first products to be released are the ERBE-Like top of atmosphere (TOA) fluxes (ES-8; ES-4; ES-9). These data are processed with the ERBE algorithms, allowing comparison to the ERBE historical data. The validated CERES ERBE-Like data are available at (eosweb.larc.nasa.gov/project/ceres/table_ceres.html). This paper compares the 1998 TRMM CERES data to the Earth Radiation Budget Satellite (ERBS) climatological TOA fluxes from 1985-1990.

3. COMPARISON OF ERBE AND CERES

In order to minimize effects from diurnal sampling, results are compared for monthly tropical mean from 20N to 20S latitude which we will call the tropical mean. An error analysis was performed using hourly GOES data subsampled using simulated TRMM and ERBS orbital passes and then compared to the full 24 hour data set (Young et al., 1998). The analysis determined the uncertainty in shortwave (SW) and longwave (LW) tropical mean fluxes expected for the ERBE-Like CERES data on TRMM, and for the ERBE data using only the ERBS precessing orbit data. TRMM precesses through all local hours every 23 days, and ERBS does the same in 36 days. For 20S to 20N, the GOES simulations indicate 1-sigma uncertainties of:

Time Sampling Uncertainty

Spacecraft Sampling	*SW Flux*	*LW Flux*
ERBE/ERBS	1.9 Wm^{-2}	0.2 Wm^{-2}
CERES/TRMM	1.4 Wm^{-2}	0.2 Wm^{-2}

These time sampling errors are sufficiently small to allow careful comparisons of the two data sets for LW fluxes, but are marginal for SW fluxes. Since both data sets are precessing orbits, angle sampling errors are expected to be similar for both data sets. Spatial sampling errors are negligible for tropical mean fluxes.

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Figure 1 shows the tropical mean longwave flux for January to August of 1998 for CERES, and the maximum, mean, and minimum values for the same months of the year from 1985 to 1989 using ERBS data.

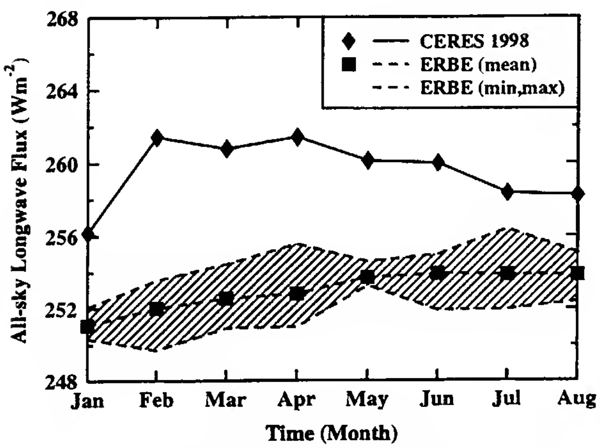

Fig. 1. Time series of CERES-TRMM and ERBE-ERBS scanner All -Sky TOA LW flux averaged 20S to 20N.

There is a large difference between the two data sets, with CERES longwave fluxes higher by 4.5 Wm^{-2} in July and August and by 9 Wm^{-2} in February. Given that the large ENSO event of 1997/8 peaked in February/March according to the NOAA/CDC Multivariate ENSO index (Wong et al., 1999) and had disappeared by July, 1998, part of this difference is apparently due to the 1998 ENSO event. Note that the diurnal sampling uncertainty of 0.2 Wm^{-2} indicates that the 95% confidence bound on tropical mean longwave flux differences of CERES and ERBE is only 0.5 Wm^{-2}. The observed difference is significant at the 10 to 20 sigma level. The largest year to year variability seen in the ERBS tropical mean LW TOA flux is 2.5 Wm^{-2}, including the relatively weaker ENSO event in 1987.

Figure 2 shows the equivalent plot for Clear-Sky LW fluxes. In this case, the differences are much

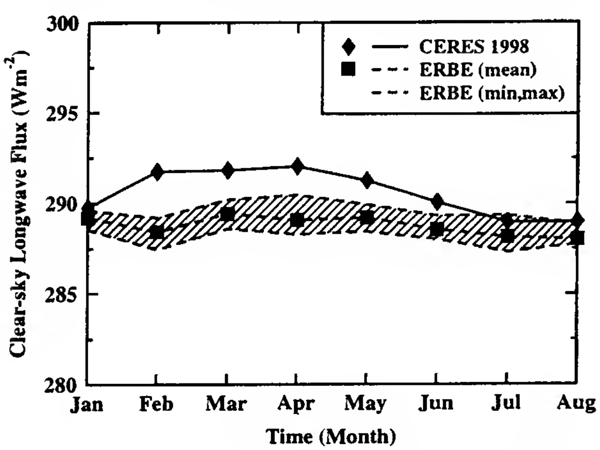

Fig. 2. Time series of CERES-TRMM and ERBE-ERBS scanner clear-sky TOA LW flux averaged 20S to 20N.

smaller and the variability appears to be dominated by the ENSO event. Wong et al. (1999) show excellent agreement between the CERES measured clear-sky LW flux anomalies over oceans and anomalies in Reynolds SST and NOAA/NCEP atmospheric temperature and water vapor. From a clear-sky perspective, the CERES and ERBE LW fluxes are consistent, with all differences explained by the 1998 ENSO event.

4. COMPARISONS TO ERBS NONSCANNER

The differences in all-sky tropical mean flux between ERBE and CERES are unexplainably large. There are arguably two major possibilities for such large differences: instrument calibration, or changes in the Earth radiation fields. Recall that the calibration of LW radiances for ERBE was considered to have an absolute accuracy of 1%, and for CERES an accuracy of 0.5% (Lee et al., 1998). If each of these instruments were operating at opposite ends of their uncertainty range, a difference of 1.5% would be possible, or roughly 4.4 Wm^{-2}, the same magnitude found in July, 1998 when the ENSO event is over. Yet the stability of the ERBE radiometer for LW radiance was found to be better than 0.5%, and CERES in the first year is better than 0.2% as indicated earlier. This suggests that like the solar constant, stability of the measurement is much better than the absolute accuracy, and that overlapping broadband measurements for climate data are critical.

Fortunately, we do have some overlap capability from ERBE to CERES. The ERBS spacecraft carried not only the ERBE scanner which operated successfully from 1985 to 1990, but also the broadband nonscanning Wide Field of View (WFOV) active cavity radiometers. These WFOV active cavities (total and shortwave channels) are utilized once every 2 weeks to perform solar constant measurements, with the remainder earth-viewing measurements. While the WFOV data have a very large field of view approaching 1000 km, these data can be used directly to examine the variability in tropical mean flux (20S to 20N) continuously from 1984 through 1998. The ERBS spacecraft is still operational, but a tape recorder anomaly in March of 1998 has delayed the processing of the ERBS WFOV data for April, 1998 and beyond. So to date, we only have two months of overlapping data between the CERES and the ERBS WFOV instrument: January and February 1998. The remaining months of 1998 should become available by summer of 1999.

Figure 3 shows the time series of ERBS WFOV monthly tropical mean LW flux anomalies from 1984 through February of 1998. Anomalies are relative to the 1985-1989 ERBE scanner data period. Figure 3 indicates that the WFOV identified an increase in tropical mean LW flux in early 1991, Pinatubo aerosols then led to a reduction in mid to late 1991, with a recovery over the following two years back to higher LW fluxes in 1993 through early 1998. In January and

February of 1998, the ERBS WFOV anomalies are 3.5 and 7.5 Wm^{-2}, consistent with the differences seen between the ERBE and CERES scanner LW fluxes.

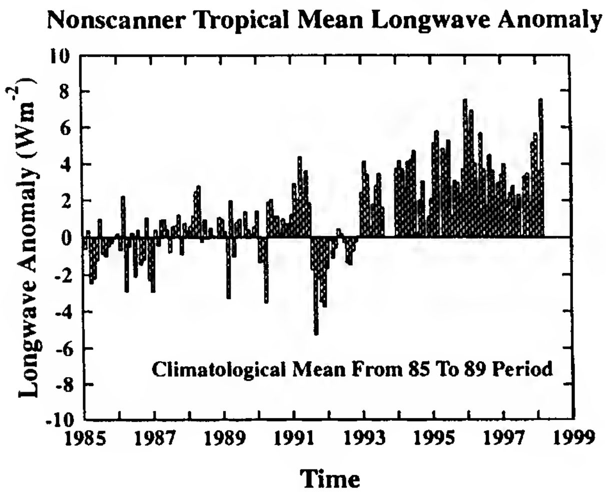

Fig. 3 Monthly mean anomalies of ERBS nonscanner WFOV all -sky TOA LW flux averaged over 20S to 20N.

We look further into the WFOV/scanner comparison by examining LW flux differences between the ERBS WFOV tropical mean and the tropical means in the same months from scanning radiometers on ERBS, ScaRaB (Scanner for Radiation Budget), and CERES. For January and February of 1985-1989 for ERBS, February 1995 for ScaRaB, and January and February 1998 for CERES, the mean and sigma are shown below (in Wm^{-2}):

Tropical Ocean Mean LW Data (20S-20N)	*Avg.*	σ
ERBS WFOV - ERBS Scanner	1.9	1.0
ERBS WFOV - ScaRaB Scanner	1.0	-
ERBS WFOV - CERES Scanner	2.4	-

These comparisons show that in fact the ERBS WFOV time series is consistent with ERBE, ScaRaB, and CERES scanner LW fluxes. Using the variability in the 10 months of ERBS WFOV minus ERBS scanner comparisons, the 95% confidence bound for 1 month of WFOV - ScaRaB data is 2.2 Wm^{-2}, and for the 2 months of WFOV - CERES data is 1.6 Wm^{-2}. We conclude that the large difference between CERES and ERBE scanner data is not consistent with calibration differences between the instruments. When April through August 1998 ERBS WFOV data become available this summer, the 95% confidence bound can be reduced further to 0.8 Wm^{-2} for CERES scanner and ERBS WFOV comparison.

Could the ERBS WFOV calibration have changed over time in such a way as to obscure ERBE, ScaRaB and CERES instrument absolute calibration differences? There are two ways to check this. First, the gain of the WFOV active cavity instruments (Total and SW channel) are verified by using the WFOV to monitor solar constant every 2 weeks during the data record. For the WFOV total channel, which provides the LW flux information, the solar constant determination is compared with overlapping independent solar constant measurements and is stable to 1 Wm^{-2} (or less than 0.1%) for the entire period of 1984-1998. More problematic for earth viewing with active cavity radiometers is the measurement offset or zero-level. The offset does change slowly in time and is verified by deep space looks every two weeks. Figure 4 shows the time series of the WFOV LW flux anomalies from Fig. 3 (dashed line) compared directly with the WFOV total channel offset time series (solid line). Sudden changes in the offsets occur when the instrument is powered off for significant periods of time. Except for these events, the WFOV instrument follows the expected slow systematic drift in offset. From Fig. 4, there is no apparent correlation between the WFOV Total channel offsets, and the tropical mean LW flux anomalies. This comparison again argues that the differences between ERBE and CERES are not calibration differences.

The robustness of the ERBS WFOV and CERES scanner comparisons will become much more convincing when the overlapping data for April through August 1998 become available.

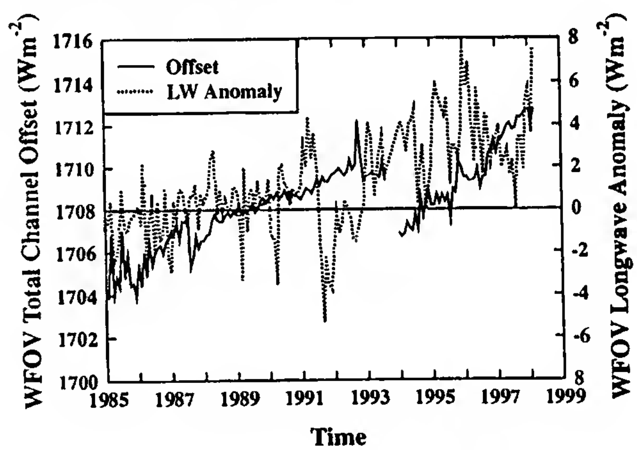

Fig. 4 Time series of ERBS nonscanning wide field of view (WFOV) total channel anomaly in tropical mean LW flux (thick line) and total channel offsets (thin line).

5. CONCLUSIONS

Examination of the climate record for broadband radiative fluxes from ERBE, ScaRaB, and now CERES indicates an apparent shift in the tropical mean (20S - 20N) all-sky LW flux at the top of the atmosphere. According to the ERBS nonscanning wide field of view data, this shift began in early 1991, 3 to 6 months prior to the Mt. Pinatubo eruption. Roughly half of the changes observed in 1998 can be explained by the large ENSO event, but by July and August of 1998, the ENSO index has returned to normal, while CERES tropical mean all-sky LW fluxes remain 4.5 Wm^{-2} higher than those in the ERBE period from 1985-1989. Unfortunately, we only have two months of overlap of

CERES and ERBS WFOV data to date. The months of April 1998 through August 1998 should become available in the next few months to further confirm the calibration tie of CERES to ERBE.

Checks of the CERES three-channel consistency (total, shortwave, window) indicate that a ~1% inconsistency in the absolute accuracy of the CERES shortwave channel or in the shortwave part of the total channel (Kratz et al., 1999) can explain 1 Wm^{-2} of the 4.5 Wm^{-2} all-sky LW July and August differences between ERBE and CERES. This leaves 3.5 Wm^{-2} unexplained. For clear-sky tropical mean LW fluxes in July and August, if we apply the same 1% SW correction we obtain a clear-sky average for CERES - ERBE of only 0.4 Wm^{-2}.

How significant are these differences given the year-to-year variability in July / August ERBE tropical mean LW all-sky and clear-sky flux seen in 1984-1989? Using a Student's-T analysis, the 95% confidence level for the July / August all-sky LW tropical flux is 2.1 Wm^{-2}, and for clear-sky LW tropical mean flux is 1.0 Wm^{-2}. We conclude that the July and August CERES all-sky LW fluxes are well outside the 95% confidence limit (3.5 vs 2.1 Wm^{-2}), while the LW clear-sky fluxes are well within the confidence limit (0.5 vs 1.0 Wm^{-2}).

The agreement in clear-sky LW values, and disagreement in all-sky LW values indicates that changes in cloud properties between the ERBE and CERES time periods are responsible for the differences. Unfortunately, the statistical significance of the SW TOA flux differences between ERBE and CERES are limited by diurnal sampling noise using single spacecraft estimates. Greatly improved SW comparisons will become available with the launch of CERES on Terra at 10:30am (July, 1999) and EOS-PM at 1:30pm (December, 2000). For July and August, the CERES - ERBE tropical mean all-sky SW flux differences are 4.3 and 1.6 Wm^{-2}, respectively, for a 2 month average of 2.9 Wm^{-2}. But the 95% confidence bound for time sampling noise alone of a 2-month average is 3.3 Wm^{-2}, and the difference is not statistically significant. Averaged over the January to August period, CERES - ERBE tropical mean SW flux difference is 2.5 Wm^{-2} with a 95% confidence bound of 2.1 Wm^{-2}. But this difference includes the large ENSO changes. Indeed, it may be possible that the July LW flux differences are still partially due to residual ENSO changes.

Unfortunately, the CERES scanner on TRMM experienced an anomaly with its voltage converter and has been used sparingly since September, 1998. It will not be returned to routine observations until the CERES instrument on Terra is turned on, probably September, 1999. The wait is to assure overlap of the TRMM and Terra CERES measurements and to thereby maintain the overlapping calibration record. Meanwhile, ScaRaB was launched in August 1998 and will provide key broadband observations of the recent La Nina event. Efforts are underway to intercalibrate the CERES and ScaRaB instruments when the TRMM and Ressurs spacecraft sample at similar local times of day (once every 23 days).

Given the apparent unexpected changes in tropical mean LW flux measured by ERBS, ScaRaB, and CERES, and given the unprecedented stability of the CERES broadband calibration, it is critical to maintain in the future an overlapped climate data set of very accurate and stable broadband radiation. Unfortunately, there is currently a gap in plans for the CERES observations between the end of EOS Terra and EOS-PM observations in 2005/6 and the beginning of CERES observations on NPOESS in 2008/9. The sampling difficulties obvious in the early CERES studies in trying to establish overlap between the ERBS WFOV data and CERES scanner data will probably not allow tying these climate records together with accuracies much better than 1 Wm^{-2}. The early stability of the CERES scanner at better than 0.25 Wm^{-2} argues that overlap of stable broadband scanning radiometer data should be capable of tracking climate change at much higher accuracies approaching 0.25 Wm^{-2}. Climate time series with data gaps will leave many questions, and achieve accuracies closer to 1-2 Wm^{-2}, marginal for climate research.

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